






# Coastal protection assessment: a tradeoff between ecological, social, and economic issues

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**Abstract.** Marine coastal ecosystems are crucial to human populations in reducing disaster risk. Least Developed Countries are particularly vulnerable to the effects of climate change, such as sea-level rise and storm surges. The Mauritanian coast, West Africa, ranks among the most vulnerable worldwide to sea-level rise, and coastal communities in the National Park of Banc d'Arguin (PNBA) are particularly at risk. Here, we assessed the service of coastal protection in PNBA by (1) mapping the coastal marine ecosystems with Sentinel-2 imagery and determining their spatial wave height attenuation rates; (2) assessing the vulnerability of villages and natural habitats to coastal hazard risk; and (3) assessing the applicability of coastal protection measures in the PNBA. We found that a total of 83% of the populated coastline presents a moderate to high risk of flooding and erosion, with Iwik and R'Gueiba being the most threatened villages in the PNBA. As for the ecological risk, two low-elevated islands, which support breeding colonies of birds, are particularly vulnerable to sea-level rise. However, in other areas, the rupture in the dune cord created new lagoons that present valuable ecological and economic interests like the Lagoon of Bellaat. Improving the comprehension of wave attenuation provided by coastal habitats, combined with identifying the vulnerability and applicability of coastal protection measures, is essential for achieving the Sendai Framework for Disaster Risk Reduction goals. In the PNBA, relocation of identified villages at risk is probably the best cost-effective solution with the least disturbance to both breeding and wintering birds. Protection of coastal ecosystems will also ensure a continued provision of other ecosystem services, including food supply for sea dependent populations, and contribute to achieving the Paris Agreement and Sustainable Development Goals.

**Key words:** bare mudflats; coastal protection; coastal vulnerability; ecosystem services; mangroves; Mauritania; National Park of Banc d'Arguin; salt marshes; seagrass beds; wave attenuation.

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## INTRODUCTION

Human populations living in low-lying coastal zones are vulnerable to coastal erosion and flooding (McGranahan et al. 2007, FitzGerald et al. 2008). In the context of global change, they are particularly threatened by the increase in frequency and magnitude of natural hazards such as storms and hurricanes (Nicholls et al. 2008, Neumann et al. 2015) combined with the average sea-level rise of 3 mm per year currently observed (Thompson et al. 2017). Those natural disasters represent a significant threat to sustainable development, especially in developing countries, where the mortality and economic losses from disasters are much higher (UNISDR 2015). Reducing disaster risk and the associated social, environmental, and economic impacts remains a global priority (Sebesvari et al. 2019), for which the Sendai Framework for Disaster Risk Reduction (SFDRR; UNISDR 2015) provides multiple targets, priority actions, and guiding principles to countries. The SFDRR emphasizes the need to address underlying causes of disaster risk and to prevent the emergence of new risks, in addition to disaster preparedness.

Coastal marine ecosystems such as mangroves, seagrass beds, coral reefs, and salt marshes are critical in reducing disaster risk in low-lying coastal zones, as they support three essential functions for coastal protection: wave attenuation, storm surge reduction, and seabed elevation (Shepard et al. 2011, Duarte et al. 2013, Ondiviela et al. 2014, Spalding et al. 2014). Indeed, the amount of waves energy reaching the shore depends on the bathymetry, the slope, and the sediment properties of the seabed (Le Hir et al. 2000). In the presence of a vegetated habitat such as seagrass beds or mangroves, the stiffness, density, leaf length, and morphology of the plants further dissipate wave energy, increase bottom shear stress (Mendez and Losada 2004, Bouma et al. 2005), and reduce current flows and turbulences (Koch et al. 2009). Belowground, the root systems secure sand fixation, allow high sediment accretion rates and shore stability. However, coastal marine ecosystems globally have seen their ecological condition and physical properties degraded by the combined effects of climate change and anthropogenic stressors such as pollution and land-use practices (Waycott

et al. 2009, Friess et al. 2016, Megonigal et al. 2016). The resulting decline in the coastal protection service they provide put coastal infrastructures and populations even more at risk in the face of climate change (Shepard et al. 2011).

To deal efficiently with disaster risks, the coastal protection provided by coastal marine ecosystems must be considered by decision- and policy-makers as part of their integrated coastal zone management plans. It requires a good understanding of all three social, economic, and ecological dimensions of the system considered (Martínez et al. 2007) and their interactions with the service of coastal protection. While the ecosystems providing coastal protection are well identified, there is still a significant knowledge gap associated with the processes involved and their complex interactions, which impedes our understanding and the quantification of this service (Bouma et al. 2014). Furthermore, one of the most common tools in ecosystem services valuation is monetary evaluation. Although it is recognized as a useful and powerful instrument (Costanza et al. 1997, Martín-López et al. 2009), it can fail to apprehend the environmental, social, and economic dimensions of the system in some contexts. Indeed, the service of coastal protection is often assessed using the replacement and avoided damages cost methods (Samonte-Tan et al. 2007, Pascal et al. 2016). On the one hand, the replacement cost approach implies the possibility of implementing artificial coastal defenses, which often has adverse impacts on the environment and society, and is therefore not always a desirable option, especially in a marine protected area (Stamsky 2005, Cooper et al. 2020). On the other hand, the damage avoided cost approach only works if there are valuable properties on the coast. However, in developing countries, the property value or repair cost does not necessarily grasp what these populations find relevant, meaningful, significant, or imperative, thus overlooking the social value of their houses (de Vries and Voß 2018). Other more inclusive approaches are therefore needed to value the coastal protection service in situations where the social value to people outweighs the mere economic value.

Over the past thirty years, climate change in Mauritania has translated into an increase in climate aridity (MEDD 2010), sudden alternation

of dry and wet years (Sultan et al. 2015), and a higher intensity of rain events (Nouaceur 2009). Combined with marine storms, these changes have led to coastal erosion, thinning of the barrier beach, and dramatic climate-related natural disasters in the country (MEDD 2010). In the National Park of Banc d'Arguin (PNBA), the population lives exclusively by the coast (Fall 2014). This local community has low education levels, low incomes that come almost exclusively from traditional fishing, have low mobility, and have little possibilities for diversifying their livelihood (Hamid 2018). Their villages are sheltered from waves energy and currents by vast tidal flats, seagrass beds, salt marshes, and mangroves. However, the shoreline equilibrium is particularly sensitive to climate change through wind patterns, current regimes, sea-level rise, and the integrity of those ecosystems. In this context, we thus decided to focus our work on the PNBA as a case study to test an approach to coastal protection assessment that considers both the ecological dimension of the service and the vulnerability of local communities and natural habitats to coastal hazards. As Mauritania is one of the Least Developed Countries in the world, we decided to use other indicators than the monetary value. First, we updated the distribution of coastal marine habitats using remote sensing techniques. Then, we characterized their respective wave attenuation capacity and other biotic parameters to understand and quantify the service of the wave attenuation function supporting coastal protection. In a second step, we assessed (1) the vulnerability of the villages to coastal hazard based on a wave energy model, the risk of flooding, the proximity to the shores, and the presence of protective natural features (e.g., seagrass beds, barrier island, cape), and (2) the ecological consequences of flooding on natural habitats. Finally, we confronted potential solutions for disaster risk reduction with the socio-economic and ecological specificities of the PNBA to implement integrated ecosystem-based management approaches that incorporate disaster risk reduction. This overall approach can be readily used in other regions of the world to help assess the service of coastal protection and strengthen the sustainable management of ecosystems to mitigate disasters.

## METHODS

### *Study area*

Located between 19°20' N and 20°30' N along the coast of Mauritania, the National Park of Banc d'Arguin (PNBA) is one of the largest protected areas in West Africa, covering 12,000 km<sup>2</sup> (Fig. 1). The southeastern part of Banc d'Arguin presents vast expanses of mudflats, mostly covered by seagrass beds (Honkoop et al. 2008). Salt marshes and mangroves have limited coverage as they both reach their southernmost and northernmost distribution in PNBA, respectively. Finally, the sebkha is a coastal, supratidal mudflat in which evaporite-saline minerals accumulate due to arid conditions. Offshore Mauritania, the swell varies from 1.7 to 2.7 m in height (Thomas and Senhoury 2007) with the main current entering the Gulf of Arguin from the north, at Cape Blanc, and flowing through the entire bank toward the south (Hanebuth and Lantzsich 2008). These currents are also driven by the tide, reaching a velocity of up to 2–3 m/s (Klicpera et al. 2015) and by strong winds of force 4–6 on the Beaufort scale (Ould Dedah 1993). Furthermore, the coastline of the PNBA is also shaped by wind-driven terrestrial inputs of sand from the Sahara through dune displacement or dune erosion (Faye 2010). Despite the harsh conditions, 1300 inhabitants, called Imraguen, live in PNBA, exclusively by the shores, distributed in eight villages along the coast (Fall 2014).

### *Mapping of coastal marine ecosystems*

To map the distribution of coastal marine ecosystems in the PNBA, we used Sentinel-2 source images from February 22, 2018, through the Copernicus program of the European Space Agency. In April 2018, a ground-truthing campaign was performed, from Cap Sainte-Anne to Cap Timiris, to build a robust training and validation sample of about 250 stations over coastal marine habitats, and to carry out their classifications on Sentinel-2 images. To define the ecological state of the communities, we used the variation of the spectral signature of one ecosystem to account for the changes in the cover density.

### *Wave attenuation capacities of coastal marine ecosystems*

The coastal protection service provided by coastal marine ecosystems in the PNBA was

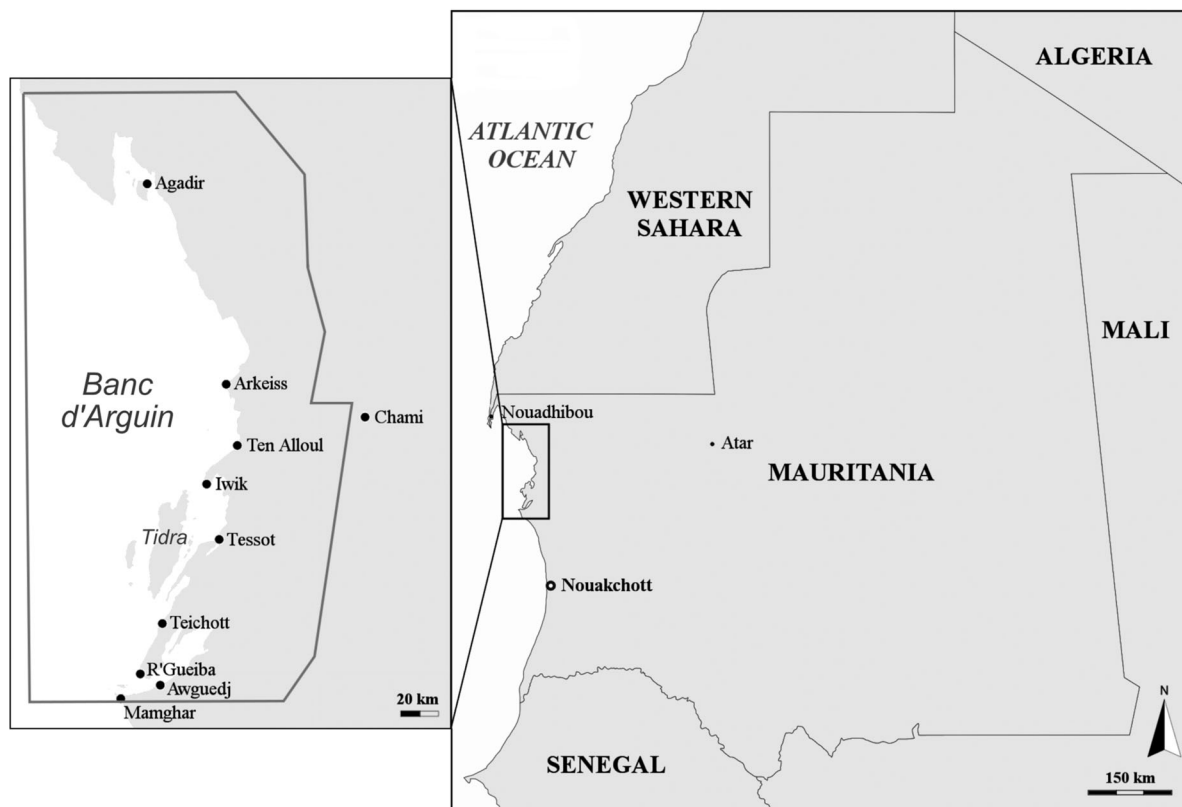


Fig. 1. Location of the National Park of Banc d'Arguin, Mauritania, West Africa.

assessed through their capacity to attenuate waves' heights, extracted from a literature review. Incoming wave height measured at wave recording stations along a cross-shore transect were collected to compute the wave height attenuation rate %A such as:

$$\%A = 100 \times \left( 1 - \frac{H_2}{H_1} \right)$$

with %A representing the wave height attenuation factor,  $H_1$  the height of the incoming wave, and  $H_2$  the wave height at the end station.

Wave attenuation rates for each marine ecosystem of the Banc d'Arguin were then modeled against the ecosystem width (cross-shore extent) using linear mixed-effect models (LMMs) with restricted maximum likelihood. Although other parameters could explain the ecosystem wave attenuation rate, the ecosystem width was the only one consistently available throughout the literature review for each %A. However, to account for the natural variability and other variables that

may interfere with wave attenuation (e.g., plant density, dominant species, canopy height and stiffness, current, slope), we only selected field experiments in our literature review. We computed the origin of the data as a random effect reflecting the individual characteristics of each ecosystem considered in these studies.

Residuals analysis did not reveal any violation of the models' assumptions of normality and homoscedasticity. Following recommendations of Bates et al. (2015), we then assessed the significance of the effect of ecosystem width on the wave attenuation rate through likelihood ratio tests (LRTs) between the fitted model and the corresponding null model, with a significance threshold of  $P < 0.05$ . Finally, we evaluated the LMMs goodness-of-fit by computing marginal and conditional  $R^2$  ( $R_m^2$  and  $R_c^2$ , respectively). Marginal  $R^2$  corresponds to the proportion of variance explained by the fixed effect (i.e., the ecosystem width). Conditional  $R^2$  corresponds to the proportion of variance explained by both the fixed and

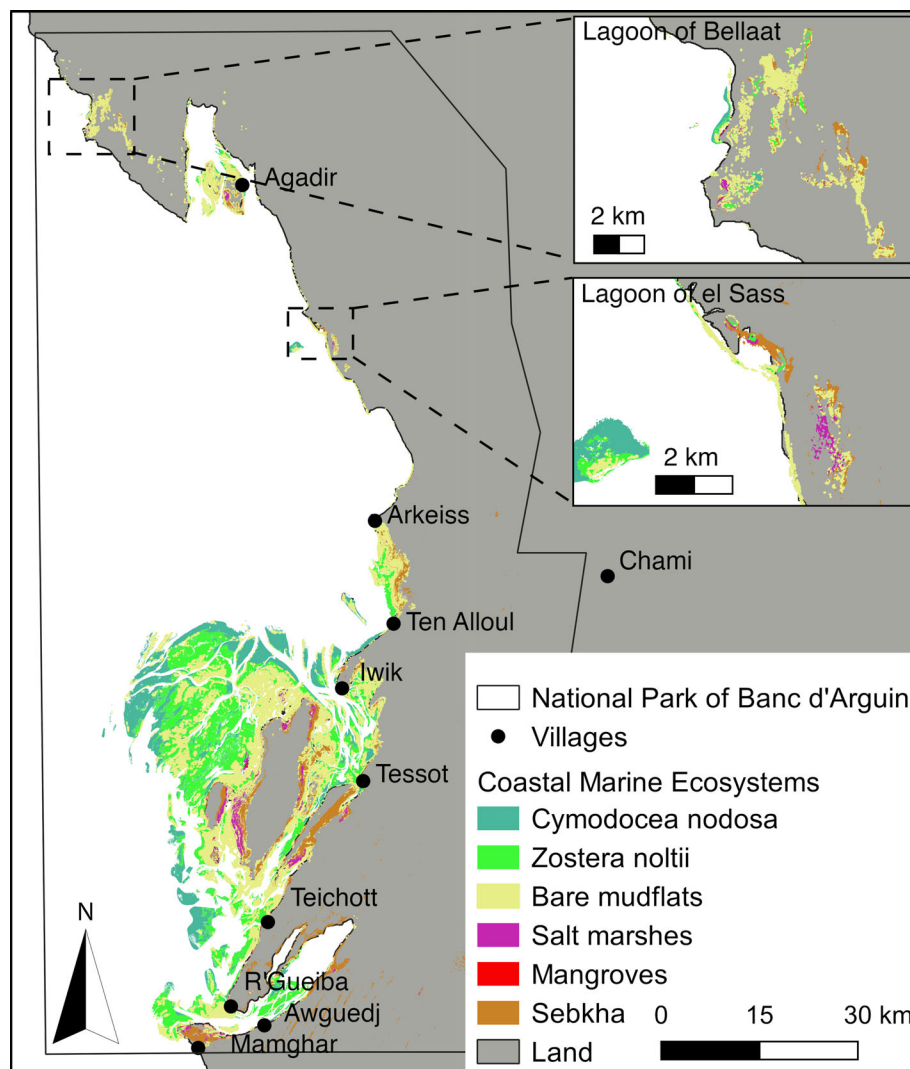


Fig. 2. Map showing the most prevailing coastal marine ecosystems in the National Park of Banc d'Arguin, Mauritania, based on Sentinel-2 imagery.

the random effect (i.e., the ecosystem width and the origin of the data reflecting other environmental parameters). For salt marshes, we noticed that most studies focused on ecosystems not exceeding 50 m in width, where high attenuation factors were observed. In comparison, salt marshes in the PNBA can reach several hundred meters in width (Fig. 2). Therefore, we fitted LMMs to the whole dataset and to the sub-dataset including only salt marshes not exceeding 50 m in width in order to gain a better understanding of the spatial dynamics of wave attenuation in salt marshes.

All analyses were computed using the R ver. 3.4.1 statistical environment (R Development Core Team 2019). We fitted the LMMs with `lmer()` (`lme4` package, Bates et al. 2015) and computed LRTs with `anova()` (`stats` package, R Development Core Team 2019). Marginal and conditional  $R^2$  were computed with `r.squaredGLMM()` (`MuMIn` package, Bartoń 2017).

To account for the variance that is not explained by the ecosystem width, we also considered plant density and dominant species in the mapping of coastal habitats (Fig. 2). We also



retrieved the canopy height and stiffness of the plants from the literature. To characterize the latter, we used Young's modulus of elasticity ( $E_T$ , N/mm<sup>2</sup>), a biomechanical property that defines the resistance to deformation (Niklas 1992).

### Coastal hazard risk and vulnerability

Here, we defined the vulnerability of PNBA's shores by identifying the goods at risk from sea-level rise, erosion, and inundation. In the PNBA, the presence of villages (human population, schools, infrastructures, roads) and unique terrestrial fauna and flora of particular importance to the region are the main assets at risk.

We assessed the vulnerability of each village to coastal hazard risk by considering the incoming wave energy, the proximity to shore, natural protective features, and the flooding risk. We assigned scores from 1 to 4 for each of these parameters, 4 indicating the highest exposure to coastal hazards for the village, as follow:

1. Wave energy: We used the wave energy model developed for the PNBA by El-Hacen and his collaborators (see El-Hacen et al. 2019 for more details). From the range of relative wave energy (J/m) in the PNBA, we assigned a score of 4 to villages exposed to the most energetic waves and 1 to villages exposed to the lowest wave energy. Equal intervals were chosen such as 1 = [0–4650 J/m], 2 = [4650–9300 J/m], 3 = [9300–13,950 J/m], and 4 = [13,950–18,600 J/m].
2. Proximity to shore: The score is based on the distance between the shore and the closest dwelling of the village, and the distance between the closest and the farthest dwelling from the shore. If the distance between the shore and the closest dwelling of the village is <50 m, we assigned a score of 2, and if the distance is more than 50 m, we assigned a score of 1. If the distance between the closest and the farthest dwelling from the shore is <200 m, we assigned a score of 2, and if the distance is more than 200 m, we assigned a score of 1. For each village, we summed both scores for a total score ranging from 2 to 4.
3. Natural protective features: The score is based on the succession of marine habitats providing a function of coastal protection

and geomorphological features (cape, island). We assigned a score of 4 if only two protective habitats are found, 3 if three protective habitats out of four are found, 2 if all protective marine habitats are found (seagrass, bare mudflats, salt marshes, mangroves), and 1 to villages that are also protected by geomorphological features.

4. Flooding: Based on the findings of Grivaud (2012), we assigned a score of 4 if villages are at high risk of flooding and a score of 1 if the risk is low.

We then averaged the scores to obtain the following vulnerability indices: low ( $1 \leq L < 2$ ), medium ( $2 \leq M < 3$ ), and high ( $3 \leq H \leq 4$ ). Note that the vulnerability to coastal hazard risk is much more complex and depends on other biophysical factors that contribute to erosion and retention (e.g., plant density and basal area, root system, coastal geomorphology, or soil stiffness).

We also identified areas in the PNBA with particular ecological vulnerability due to the topography and the presence of emblematic or endangered species. We used remote sensing images from 1984 to 2018 (Google Earth and Worldview) to retrace the episodes of flooding and the creation of the lagoons. Moreover, we identified low-elevated islands in the PNBA that support important breeding bird colonies, at risk of flooding.

## RESULTS

### Maps of ecosystems and ecological condition

The coastal marine ecosystems of the PNBA consist mainly of seagrass beds (674.2 km<sup>2</sup>) and bare mudflats (121.2 km<sup>2</sup>). Two phanerogams species dominate seagrass beds in the

Table 1. Surface areas (km<sup>2</sup>) of vegetated marine habitats per shoot density category in the National Park of Banc d'Arguin, Mauritania.

Ecosystems	Shoot density			Total
	Low	Medium	High	
Seagrass <i>C. nodosa</i>	144.7	55.4	21.6	221.7
Seagrass <i>Z. noltii</i>	163.4	218.7	70.4	452.5
Salt marshes	11.4	14.7	NA	26.1
Mangroves	0.6	0.3	0.1	1.0

Table 2. Morphological and biomechanical properties of *Zostera noltii*, *Cymodocea nodosa*, *Spartina maritima*, and *Avicennia germinans*.

Morphological and biomechanical properties	Seagrass <i>Z. noltii</i>	Seagrass <i>C. nodosa</i>	Salt marshes <i>S. maritima</i>	Mangroves <i>A. germinans</i>
Plant height (cm)	5–25†	10–45†	20–70	30–480#
Leaf length (cm)	5–25†	10–45†	10–40	9–12¶¶
Leaf width (mm)	0.5–2†	2–4†	5–10	30–50
Rhizome thickness (mm)	0.5–2†	3†	NA	NA
Young modulus of elasticity ( $E_T$ , N.mm <sup>-2</sup> )	119.6–166.9‡	58.7–91.8§	1410.0¶,‡‡	16,690.0†,§§

Note: Average range values are indicated.

† Ondiviela et al. (2014)

‡ La Nafie et al. (2012)

§ De los Santos et al. (2013)

¶ Feagin et al. (2011)

# Dahdouh-Guebas and Koedam (2001)

|| Gonçalves-Alvim et al. (2001)

†† Manguriu et al. (2013).

‡‡ In the absence of data for local species, we used data from *Spartina alterniflora* instead.

§§ In the absence of data for local species, we used data from *Rhizophora mucronata* instead.

¶¶ Zhang et al. (2013).

PNBA. *Cymodocea nodosa* is subtidal and covers 221.8 km<sup>2</sup>, while *Zostera noltii* is intertidal and covers 452.4 km<sup>2</sup>. Further up the shore, salt marshes and mangroves cover 26.1 and 0.8 km<sup>2</sup> (Fig. 2). The surfaces of each community and their respective ecological state reflected by shoot density proxy are detailed in Table 1.

#### Biomechanical properties and wave attenuation rate of marine ecosystems

The morphological and biomechanical traits of the dominant plants present in the PNBA are described in Table 2. The length and width of the leaves and the thickness of the rhizome of *C. nodosa* are larger than *Z. noltii*; however, the Young modulus of elasticity,  $E_T$ , indicates that *Z. noltii* is stiffer than *C. nodosa* (almost twice as much). Saltmarsh species *S. maritima* and mangrove species *A. germinans* present excellent biomechanical properties to attenuate wave energy, according to the plants' heights, leaf widths, and more importantly, the stiffness, with a Young modulus of elasticity,  $E_T$ , of 1410 (*S. alterniflora*) and 16,690 N/mm<sup>2</sup> (*Rhizophora mucronata*), respectively. However, mangroves of West Africa reach their most northern distribution in the PNBA and present a very low above-ground biomass (Dahdouh-Guebas and Koedam 2001, Fatoyinbo and Simard 2013), making them less efficient in the attenuation of waves than tropical mangroves (Komiyama et al. 2008).

Estimates of LMMs of wave attenuation factors for each ecosystem of the PNBA are presented in Table 3, along with the results of LRTs against the corresponding null models. Seagrass bed width significantly explained the proportion of wave height attenuation by the ecosystem ( $\chi^2_1 = 15.392$ ,  $P < 0.001$ ) following a linear relationship (Fig. 3a). Indeed, the width of the ecosystem explained more than 75% of the variance observed in the wave attenuation factor ( $R^2_m = 0.769$ ) with other environmental parameters explaining an extra 6% of the variance observed ( $R^2_c = 0.830$ ). The width of bare mudflats also significantly explained the proportion of wave attenuation ( $\chi^2_1 = 13.133$ ,  $P < 0.001$ ) following a similar linear relationship (Fig. 3b). However, seagrass beds' wave attenuation factor increased about 14 times faster with the ecosystem width than bare mudflats. The width of bare mudflats explained more than 70% of the variance observed in the wave attenuation factor ( $R^2_m = 0.736$ ) with other environmental parameters explaining an extra 15% of the variance observed ( $R^2_c = 0.886$ ).

The width of salt marshes and mangroves also significantly explained the proportion of wave height reduction ( $\chi^2_1 = 24.267$ ,  $P < 0.001$ , and  $\chi^2_1 = 37.523$ ,  $P < 0.001$ , respectively) although following a logarithmic relationship for both ecosystems in this instance (Fig. 3c, d). The attenuation of wave height by salt marshes was very efficient in the first few meters of the

Table 3. Results from the linear mixed models of the wave attenuation factor and likelihood ratio tests with null models for coastal marine ecosystems.

Ecosystems	Estimate	SE	<i>t</i>	$\chi^2$	df	<i>P</i>
(a) Seagrass beds						
Intercept	2.660	4.428	0.601			
Ecosystem width	0.188	0.032	5.882	15.392	1	<0.001
(b) Bare mudflats						
Intercept	15.622	4.804	3.252			
Ecosystem width	0.013	0.003	4.655	13.133	1	<0.001
(c) Salt marshes						
Intercept	9.563	9.208	1.039			
Ln(Ecosystem width)	13.044	2.468	5.285	24.267	1	<0.001
Salt marshes < 50 m						
Intercept	24.251	7.750	3.129			
Ecosystem width	1.457	0.239	6.086	27.092	1	<0.001
(d) Mangroves						
Intercept	-55.387	7.628	-7.261			
Ln(Ecosystem width)	23.098	1.344	17.187	37.523	1	<0.001

Note: (a) seagrass beds ( $n = 10$  observations), (b) bare mudflats ( $n = 10$  observations), (c) salt marshes ( $n = 104/92$  observations), and (d) mangroves ( $n = 21$  observations).

ecosystem (49% over 20 m), compared to mangroves (14% over 20 m), before slowing down around 60 m into the ecosystem (Fig. 3c). However, the width of salt marshes explained only 26% of the variance observed in the wave attenuation factor ( $R_m^2 = 0.259$ ) with other environmental parameters explaining an extra 20% of the variance observed ( $R_c^2 = 0.464$ ). Finally, the width of mangroves explained 52% of the variance observed in the wave attenuation factor ( $R_m^2 = 0.525$ ) with other environmental parameters explaining an extra 46% of the variance observed ( $R_c^2 = 0.979$ ).

It is worth noticing that most studies have focused on salt marshes not exceeding 50 m in width and where a high variability in wave height attenuation was observed (Fig. 3c). When fitting an LMM to the subset of data for an ecosystem width inferior to 50 m, the relationship between the wave attenuation factor and the salt marsh width remained significant although becoming linear ( $\chi^2_1 = 27.092$ ,  $P < 0.001$ ). The width of the ecosystem explained the same proportion of the variance observed in the wave attenuation factor ( $R_m^2 = 0.240$ ), but other environmental parameters explained a greater extra proportion of the variance ( $R_c^2 = 0.557$ ). Furthermore, the wave attenuation factor increased about 3.6 times faster between 20 and 50 m than when considering the whole dataset.

#### Vulnerability of villages and natural habitats to coastal hazard

*Vulnerability of villages.*—According to the spatial relative wave energy model in the PNBA, Arkeiss and Ten Alloul are the villages exposed to the most energetic waves (Fig. 4), followed by Iwik and Agadir. The other villages located further south are more sheltered from waves' energy that usually reaches <4650 J/m. Given the topography, three regions in the PNBA are at risk of coastal flooding from sea-level rise: the peninsula of Tintan and Arguin Bay, the peninsula of Iwik and Aouatif Bay, Cape Timiris, and St Jean Bay (Grivaud 2012). Coastal flooding events have indeed been recorded in the past in the villages of Agadir (Arguin Bay), Iwik (peninsula of Iwik), R'Gueiba, and Mamghar (Cape Timiris). When we combined the risk of flooding, the wave energy reaching the shores, the proximity to shores, and the presence of natural protective features, Tessot is the least vulnerable village in the PNBA to coastal hazards. Agadir, Mamghar, Teichott, Arkeiss, and Ten Alloul present a moderate vulnerability, from 2 to 2.8 out of 4. Despite the risk of coastal flooding, Mamghar benefits from low exposure to waves and the succession of coastal marine habitats protecting its coast. Finally, Iwik and R'Gueiba are the most vulnerable villages to coastal erosion and flooding with a rating of 3.5 and 3.3, respectively (Table 4), given their location



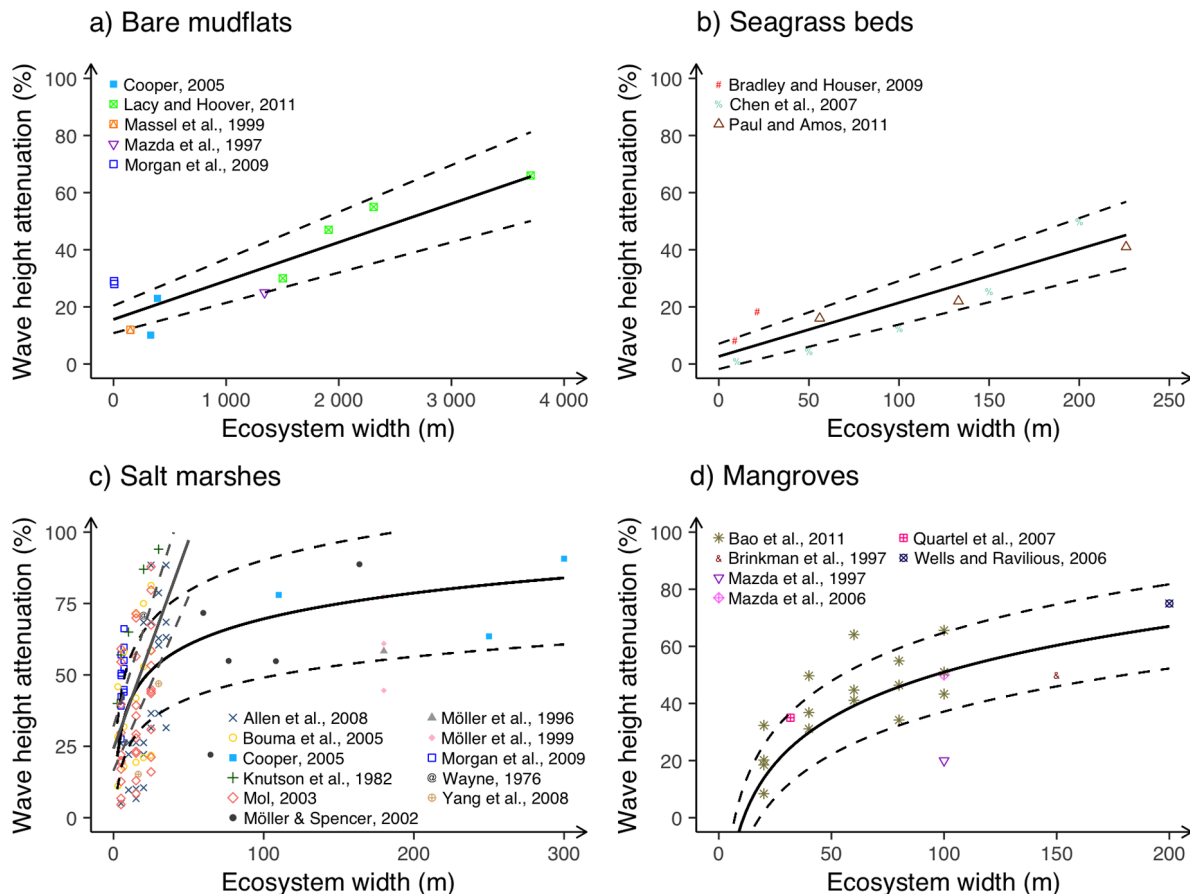


Fig. 3. Wave height attenuation rate by the width of marine ecosystems from linear mixed models for (a) seagrass beds, (b) mudflats, (c) salt marshes (gray lines indicate the LMM fitted for an ecosystem width <50 m), and (d) mangroves. Dotted lined indicates the standard error of LMMs estimates.

on a peninsula, their exposure to oceanic swell and currents, and the risk of flooding.

Villages cover 3.7 km out of 180 km of coastline in the PNBA. The risk of flooding concerns 2.3 km of coastline, but overall 3.3 km of coastline show a moderate to high vulnerability to coastal hazards, and 1 km concerns villages of high vulnerability, representing 27% of the populated coastline in the PNBA.

**Ecological vulnerability.**—Outside the villages, severe erosion processes have been noticeable at Cape Saint-Anne between 1988 and the present day, due to the rupture of the barrier beach dune cord caused by heavy rains that resulted in the formation of the Lagoon of Bellaat in 2013 (Fig. 5, upper panel). Another lagoon located in the south of Cape el Sass appeared between 2008 and 2009 according to historical satellite images.

This lagoon will be referred to as “Lagoon of el Sass” hereafter (Fig. 5, lower panel).

Finally, low-elevated sandy islands such as Nair, Toufat, and Zira are particularly vulnerable to sea-level rise, and the presence of nesting bird colonies is a significant ecological issue (Veen et al. 2018). The Mauritanian Spoonbill (*Platalea leucorodia balsaci*) and the Slender-billed Gull (*Larus genei*) breed mostly on the threatened island of Nair (north of Tidra). Breeding colonies of the same species are also found on the island of Zira, south of Iwik, along with colonies of the Caspian Tern (*Hydroprogne caspia*), the Royal Tern (*Thalasseus maximus*), and the White-breasted Cormorant (*Phalacrocorax lucidus*) (Fig. 6). Toufat is another island in the south of the PNBA that was used in the past by these species to breed before becoming deserted due to extreme flooding events.

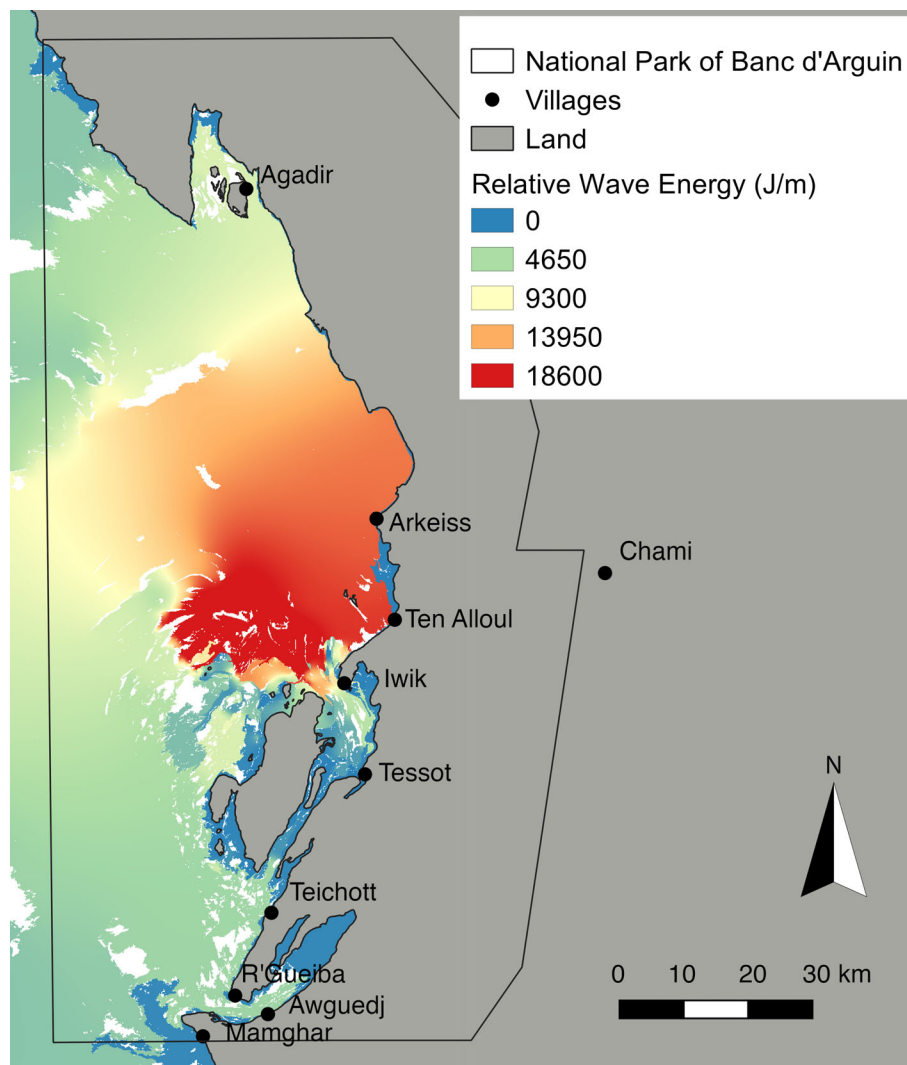


Fig. 4. Spatial relative wave energy in the National Park of Banc d'Arguin (J/m) calculated with the wave energy model (WEMo).

Furthermore, the local subspecies of the Eurasian Spoonbill, the Mauritanian Spoonbill (Piersma et al. 2012), is an endemic breeding bird to the PNBA (El-Hacen et al. 2013) whose population is in sharp decline, continuously decreasing between 1980 and 2017 (Oudman et al. 2020). One of the most important nesting sites of this subspecies is on the island of Nair. The birds build their nests on the vegetation that lines the fragile dunes acting as a natural barrier. In recent years, the sea has been gaining ground on the island of Nair and progressively flooding nests, potentially decreasing the breeding success for the species.

## DISCUSSION

### *Waves attenuation capacity of coastal marine ecosystems and disaster risk reduction*

This study highlights the capacity of mudflats, seagrass beds, salt marshes, and mangroves to absorb wave energy according to the cross-shore distance. The strong attenuation of the wave height in the first 50 m by salt marshes (61%) and mangroves (35%) is due to the stiffness and the height of the plants relative to the low water depth at high tide. The wave height attenuation was linear for mudflats and seagrass beds but

Table 4. Vulnerability of PNBA villages to coastal hazard risk in the National Park of Banc d'Arguin, Mauritania.

Villages (Coastline, km)	Relative wave energy	Risk of flooding	Proximity to the shore	Natural protection	Vulnerability to coastal hazards
Iwik (0.4)	3	4	4 (5–120 m)	3 (S + SM + BM)	3.5
R'Gueiba (0.7)	1	4	4 (15–180 m)	4 (S + BM)	3.25
Agadir (0.4)	2	4	4 (17–128 m)	1 (S + I)	2.75
Ten Alloul (0.2)	4	1	4 (25–200 m)	1 (S + I)	2.5
Arkeiss (0.3)	4	1	2 (70–400 m)	1 (C + S)	2
Teichott (0.5)	1	1	4 (10–173 m)	2 (S + SM + M + BM)	2
Mamghar (0.8)	1	4	2 (84–475 m)	1 (C + S + SM + M + BM)	2
Tessot (0.4)	1	1	3 (25–471 m)	1 (S + I)	1.5

Notes: The vulnerability score is the average of all scores. Coastline corresponds to the linear extent of dwellings along the coast (expressed in km).

Relative wave energy: 1 [0–4650 J/m]; 2 [4650–9300 J/m]; 3 [9300–13,950 J/m]; 4 [13,950–18,600 J/m]. Risk of flooding adapted from (Grivaud 2012). Proximity to the shore corresponds to the distance separating dwellings and infrastructures to the coast (expressed as shortest distance – longest distance in m). Natural protection brings together the natural elements providing a coastal protection function (BM, bare mudflats; C, cape; I, islands; M, mangroves; S, seagrasses; SM, salt marshes).

confirmed that seagrass beds exert significant control on wave heights over relatively short distances compared to mudflats. Considering the full range of ecosystems widths that can be found in the natural world is important to account for the non-linearity of the wave attenuation function (Koch et al. 2009) to avoid the risk of overestimation when extrapolating to broader ecosystems. Moreover, further studies are needed to fully understand the wave attenuation capacities of connected ecosystems. Understanding how sub- and intertidal habitats are connected and can facilitate each other directly and indirectly is still mostly unknown. For instance, seagrass beds can directly facilitate ecosystems higher up in the intertidal, by attenuating wave energy, stabilizing the sediment, and facilitating accumulation. The change in bathymetry and thereby the hydrodynamics can positively or negatively affect the ecosystem further up the intertidal (Bouma et al. 2014). Similarly, the effect of sea-level rise on each ecosystem, whether it contributes to accretion or erosion, will depend on the ability of each ecosystem to adapt or move inland, with consequences on the associated ecosystems and the frequency of flooding events (Nicholls and Cazenave 2010, Taherkhani et al. 2020).

#### Vulnerability to coastal hazard risk

Coastal protection might not be seen as a priority for decision-makers in the PNBA, given the low proportion of populated coastline. However,

Iwik and R'Gueiba are the villages that, by their orientation to the oceanic swell and currents, the proximity of dwellings to the coast, and the historical episodes of flooding, present the highest coastal risks. Additionally, their geographical positions at the tip of a peninsula are subject to significant sedimentary movements accentuated by the channels along the coast. Those two villages are essential in the PNBA. Among other assets, Iwik has a central location in the PNBA, provides easy access to fishing zones in the north of Tidra island, and has the facilities to welcome most visitors and researchers. The village of R'Gueiba hosts the shipyard of the PNBA for the construction of the Canarian lanches, the traditional fishers' boats, and provides easy access to fishing zones around Mamghar and the South of Tidra island.

Coastal marine ecosystems also protect important nesting bird colonies on low-elevated sandy islands (Nair and Zira). It must be acknowledged that all species breeding on those islands provide numerous provisioning, supporting, regulating, and cultural services to humans (Sekercioglu 2006, Cornet C.C, Trégarot E. and Failler P., *unpublished manuscript*). The most apparent service for the local population being the role played by piscivorous birds as an indicator for fish stock (i.e., *Sardinella* sp.) and as a visual guide for fishers. Given their high mobility, they not only provide ecosystem services in Mauritania but in all other countries along the East Atlantic Flyway, at least. According to Veen et al. (2018), all five species of birds that breed on the islands of Nair and Zira

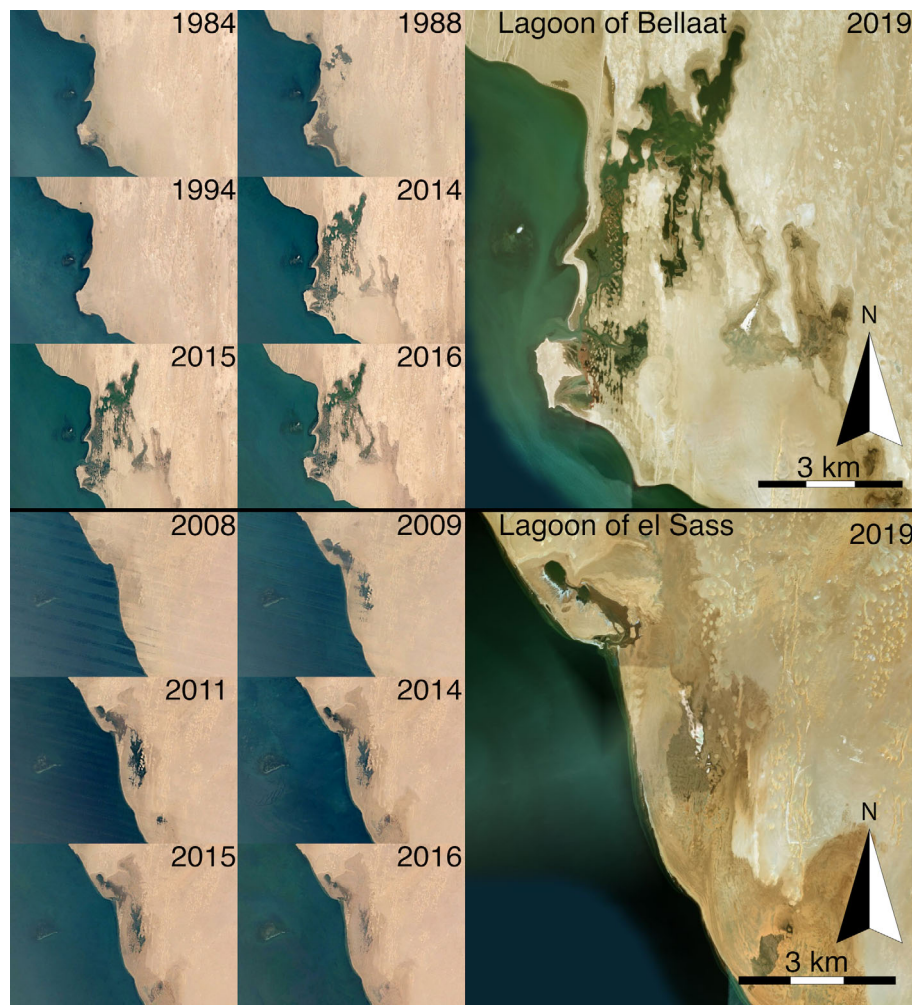


Fig. 5. Satellite images of the recently formed lagoons in the National Park of Banc d'Arguin, Mauritania. Upper panel: Lagoon of Bellaat; Lower panel: Lagoon of el Sass; on the left of the panels: historical images from Google Earth; on the right of the panels: most recent image from Worldview, 2019.

(the Mauritanian Spoonbill, the Slender-billed Gull, the Caspian and Royal Terns, and the White-breasted Cormorant) could be suitable indicators of fish biodiversity and environmental change.

When no particular goods are threatened, a breach in the shoreline could result in an ecologically and economically valuable lagoon. The Lagoon of Bellaat in Cape Sainte-Anne is a good example, and further south, the Lagoon el Sass might just as well become ecologically and economically interesting if environmental conditions (temperature, salinity, oxygen) became suitable for the development of seagrass beds. On the coast of Mauritania, this type of breach can

happen in winter but usually gets closed again after a few months. The 2013 breach in Cap Saint-Anne has not closed yet, and the Lagoon of Bellaat is flooded at each high tide. The sebkha formerly present in 2012 has become a permanent lagoon with the development of algae and seagrass beds and attracting a diverse fauna of mollusks, fishes, elasmobranchs (guitarfish), and birds (authors' observations). This exceptional situation complexifies the assessment of the service of coastal protection in the PNBA and, more broadly, in Mauritania, as the breakage of the dune belt could result in an ecologically and economically valuable lagoon.



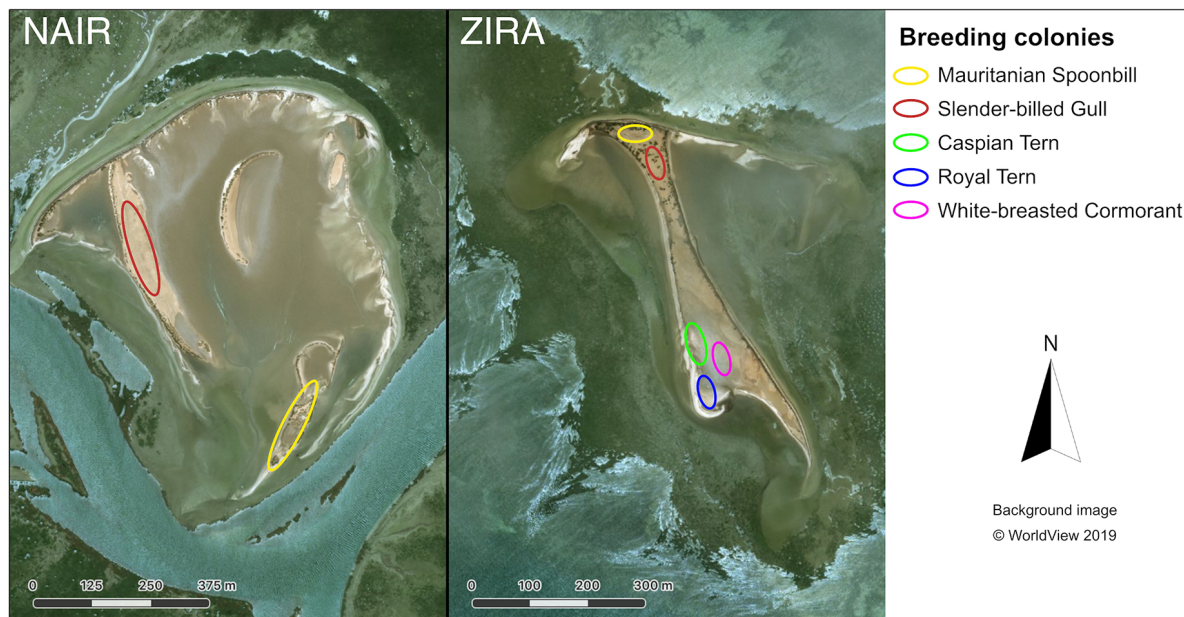


Fig. 6. Breeding colonies at risk of flooding in the National Park of Banc d'Arguin. Adapted from Veen et al. (2018).

#### Management of coastal hazards

Management strategies for coastal erosion depend on the natural and anthropogenic context. The risk of erosion arises from the confrontation between natural hazards and stakes. There is no reason to remedy erosion if there is no risk (De la Torre et al. 2014). In the PNBA, the vast majority of the coastline is not built. Therefore, local authorities must preserve the space necessary for the natural evolution of the coast and maintain favorable environmental conditions for marine ecosystems to provide coastal protection where needed. In response to sea-level rise, wetland ecosystems are expected to migrate landwards but might be constrained by low-lying human-built areas, inducing a coastal squeeze (Borchert et al. 2018). When social, economic, and ecological goods are threatened, two main strategies should be considered (Table 5).

1. The reduction of hazard by protecting the coastline from natural events using heavy means (e.g., seawalls, dikes, and levees) or limiting intervention, called soft solutions such as artificial reloading in sediment, drainage, by-passing, geotextile work, management of the dune.

2. The reduction of the stakes at risk either by a strategic retreat (i.e., giving the necessary space for the natural evolution of the littoral) or adapting to the sea-level rise (e.g., constructions on stilts).

The relocation of people would be the initial solution to consider in the PNBA, starting with a cost-benefit analysis. If relocation of goods is not possible, heavy or soft protections could be considered. However, for a site classified as National Park, RAMSAR site, and belonging to the UNESCO World Heritage, hard solutions are not conceivable. Among the soft solutions applicable in the PNBA, we can mention the restoration or rehabilitation of lost or damaged habitats. Restorative experiments for *Zostera marina* sea-grass beds have already taken place on a large scale and have shown a high success rate (Marion and Orth 2010). The flooding risk to the breeding colonies of the Mauritanian Spoonbill also led PNBA managers to put in place some protection measures such as the building of wooden nest platforms. Moreover, soft solutions were implemented with sandbags to consolidate the dunes on the island of Nair, for a total cost of



Table 5. Coastal hazard risk management strategies and feasibility in the National Park of Banc d'Arguin, Mauritania.

Strategies	Solutions	Feasibility	Justification
Hazard reduction	Heavy solutions (e.g., seawalls, dikes, and levees)	Low	Ecological and landscape disturbances too important for a National Park. Construction and maintenance costs are prohibitive.
	Soft solutions (e.g., geotextile work)	Medium	Cost-benefit analysis to be done compared to the relocation of dwellings.
Stakes reductions	Relocation of dwellings	High	Progressive solution with the evolution of the coastline. No ecological disturbance. No landscape deterioration. Proximity of the Imraguens to the sea maintained.
	Adaptation of the seaside	Low	Muddy shores of the seaside. Adapting housing and infrastructures on stilts is more restrictive than relocation.

1500 € or 60,695 MRU in 2019 (<https://www.ecofund.org/project/spoonbills-of-nair.html>). The responsibility of the preservation of this endangered bird species lies entirely on the shoulders of PNBA managers as they occur nowhere else in the world.

The strong Imraguen dependence on the sea implies that, in the event of relocation, they should be relocated close to the coast. The traditional culture of the Imraguen is part of the natural heritage of the Park and should be considered in the event of relocation. In these circumstances, the Imraguen would be some of the millions of people around the world displaced by sea-level rise (UNDP 2008). The climate refugee status would require all the assistance and the financial support necessary to relocate the dwellings. Moreover, the displacement of Imraguen might not be as easy as they belong to different tribes with fixed geographical and fishing zones within the PNBA.

#### *Is monetarization necessary?*

Depending on the type of coastal protective measures considered, the monetary value of the service of coastal protection varies. The replacement cost method would require the unit value per kilometer of heavy or soft solutions designed to replace the coastal protection function of the vegetated marine habitats (Burke et al. 2008). The damage avoided method could use the cost of relocating the dwellings, the cost to adapt to the seaside, or the cost to repair the dwellings. The case of the PNBA demonstrates that it is not always justified to protect the entire coastline from natural erosion. A breach in the dune cords could

generate ecological and economic interests, making the current approaches inappropriate to calculate a monetary value of coastal protection. Moreover, many of the poorest Least Developed Countries have informal and subsistence economies, making market-price and market-cost-based approaches meaningless or distorted (Christie et al. 2012).

In the Least Developed Countries and Small Islands Developing States at risk of coastal hazard where the social and environmental values outweigh the economic value, local authorities could use the capacity of wave attenuation by ecosystems and the vulnerability indices to strengthen the case for the application of hazard mitigation funds to engage in conservation and restoration in areas with both high flood exposure and high conservation value. In terms of land-use planning, the identification of vulnerable areas and refuge areas that are more likely to cope with the sea-level rise or storm surge by the presence of specific ecosystems might be more convincing to decision-makers than an overall monetary value that is not supported with strong communication and engagement strategies (Guerrey et al. 2015).

## CONCLUSIONS

The development of models of wave attenuation rates in this study is a pivotal milestone in assessing the service of coastal protection provided by coastal marine ecosystems. Those models can be easily applied in other regions of the world or replicated for other ecosystems, for instance, coral reefs coastal protection according to the reef flat width (Ferrario et al. 2014) and

structure (Harris et al. 2018), as long as the mapping of ecosystems is available. Models and vulnerability to coastal hazard risk can be further adjusted according to local geomorphic settings, waves and current data, and biophysical factors (e.g., shoot density, leaves lengths, plants heights, and root systems) affecting erosion, retention, and shoreline stabilization (Christianen et al. 2013, Spalding et al. 2014).

Understanding disaster risk in all its dimensions of vulnerability, exposure of persons and assets, hazard characteristics, and the environment is the SFDRR's top Priority (UNISDR 2015). Such knowledge is essential to inform policy-makers and to help the competent authorities designing cost-effective hazard reduction solutions for appropriate preparedness and effective response to disasters. The loss and degradation of coastal marine habitat have direct implications for the progress toward achieving the SFDRR goals, hence the importance to monitor loss and damage of ecosystems but more importantly, protecting coastal marine ecosystems for aligning the goals of the Sendai Framework with the ones from the Paris Agreement and the Sustainable Development Goals.

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